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METHANE EMISSION FROM ANIMALS: A GLOBAL HIGH-RESOLUTION DATA BASE

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Abstract. We present a high-resolution global data base of animal population densities and associated methane emission. Statistics on animal populations from the Food and Agriculture Organization and other sources have been compiled. Animals were distributed using a 1° resolution data base of countries of the world and a 1° resolution data base of land use. The animals included are cattle and dairy cows, water buffalo, sheep, goats, camels, pigs, horses and caribou. Published estimates of methane production from each type of animal have been applied to the animal populations to yield a global distribution of annual methane emission by animals. There is large spatial variability in the distribution of animal populations and their methane emissions. Emission rates greater than 5000 kg CH_4 $km^{-2}yr^{-1}$ are found in small regions such as Bangladesh, the Benelux countries, parts of northern India, and New Zealand. Of the global annual emission of 75.8 Tg CH_4 for 1984, about 55% is concentrated between 25°N and 55°N, a significant contribution to the observed north-south gradient of atmospheric methane concentration. A magnetic tape of the global data bases is available from the authors.

1. INTRODUCTION

Atmospheric methane plays an important role in the Earth's radiative budget and atmospheric chemistry. Its abundance was 1627 parts per billion by volume (ppbv) (4500–4600 Tg) in 1984 [Steele et al., 1987] and has been increasing at ~1% annually for the last decade [Blake and Rowland, 1986]. The budget of methane has been analyzed by many authors [e.g., Ehhalt and Schmidt, 1978; Khalil and Rasmussen, 1983; Seiler, 1984; McElroy and Wofsy, 1986; Bingemer and Crutzen, 1987]. The major methane sources include enteric fermentation of carbohydrates by ruminants, anaerobic decomposition of organic material in natural wetlands, land fills, and rice paddies, partial combustion of biomass, and emissions associated with the production, transport and combustion of fossil fuel. These sources have been estimated to contribute 500±200 Tg/yr to the total methane budget, although the contribution of each individual source is highly uncertain.

Other attempts to understand the methane budget have used two-dimensional models in conjunction with observations of methane concentrations at a few locations [e.g. Crutzen and Gidel, 1983; Blake and Rowland, 1986; Fraser et al., 1986]. While these studies have improved our understanding of the methane cycle, they have been limited by the lack of global data on the distribution of atmospheric methane. Since 1983, there has been a coherent effort by the Geophysical Monitoring for Climatic Change (GMCC) program of the National Oceanic and Atmospheric Administration (NOAA) to determine the global distribution of methane in the atmosphere [Steele et al., 1987]. Air samples are collected weekly from 23 globally distributed sites in the NOAA/GMCC cooperative sampling network. These observations represent the first global description of seasonal variations in atmospheric methane. They show that methane concentrations exhibit large latitudinal and seasonal variations in addition to the secular trend. Annually averaged methane concentrations are highest in the northern hemisphere around 70°N and decrease by ~100 ppbv to ~10°S. There is little latitudinal variation in the southern hemisphere.

These observations of the geographic and temporal variations of atmospheric methane provide new constraints

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on components of the methane budget. Implicit in the variations is information about the methane sources and sinks. In order to extract this information, we have initiated an effort to document the geographic and temporal distribution of the better known individual sources and sinks [Matthews and Fung, 1987]. These source/sink distributions will be used as inputs to global, two-dimensional and three-dimensional atmospheric tracer transport models to test various hypotheses about other sources and sinks.

In this paper, we focus on the global distribution of methane-producing domestic animals. This source of methane has been estimated to be 70–100 Tg/yr [Baker-Blocker et al., 1977; Sheppard et al., 1982; Blake, 1984] and 100–220 Tg/yr [Ehhalt, 1974; Ehhalt and Schmidt, 1978]. These authors obtained animal population statistics from the Food and Agriculture Organization (FAO) of the United Nations. The differences in the estimates of methane emission arise from the combined effect of differences in animal populations over time and of differences in assumptions about emission rates by the animals. Recently, Crutzen et al. [1986, hereafter referred to as CAS] presented a comprehensive summary of the methodology to derive methane emission rates from ruminants, and the uncertainties contained therein. They estimated that animals produced 72–99 Tg in 1983.

We present a series of global high-resolution geographic data bases of population densities of the major methane-producing animals. Included are nondairy cattle, dairy cows, water buffalo, sheep, goats, camels, pigs, horses, and caribou. The distribution of total annual methane emission by animals was obtained using the emission rates derived by CAS. The emphasis of this study is the geographic distribution of the emission rather than a reevaluation of the animals' contribution to the global methane budget. In addition to being useful for two- and three-dimensional modeling studies, geographic information about methane sources will aid in the interpretation of station measurements of atmospheric methane and in the design of measurement strategies. A magnetic tape of the global data bases is available from the authors.

2. METHODOLOGY

The FAO provides, for each country in the world, yearly population statistics for domestic animals. Estimates on populations of wild and domestic caribou are available from other sources discussed below. To obtain the geographic distributions, each animal population from FAO was mapped onto a 1° latitude by longitude resolution digital data set of countries, some of which are divided into states or regions. Within a region or country, the animal populations were distributed according to a land-use data base identifying agricultural areas associated with domestic animals. The distribution of caribou was a special case and is discussed below. Methane emission rates derived by CAS were applied to the population distributions to yield the global distribution of methane emission. The data bases are described below.

2.1. *Country Data Base*

A 1° digital data base of countries of the world has been compiled at the NASA Goddard Institute for Space Studies (GISS). This data base consists of 187 countries; seven large countries are further subdivided into smaller political entities. The subdivided countries are Australia (seven states), Brazil (five regions), Canada (10 divisions), China (29 provinces), India (25 divisions), USA (50 states, with territories and possessions treated separately), and the USSR (15 republics). The criterion for including a 1° cell in the data base was that it contain either at least 50% land or a small country not identified in any other cell. Except for the addition of a few island countries listed by FAO, the data base conforms with the modified Scripps 1° land/water data base [Gates and Nelson, 1975] used in the GISS General Circulation Model [Hansen et al., 1983]. Our computed areas are generally within 1% of published areas [FAO, 1985] for large countries and within 5% for medium-sized ones.

Each 1° cell has an integer code that is identified by use of a master list containing the name of each country or subdivision and its corresponding code. The code for each country is a multiple of 100, so that the last two digits are zero. The first digits of each subdivision are the same as those of its country; the last two digits identify the subdivision. For example, on the master list, the code for India is 7700, the code for the state of Punjab is 7718, and the 1° data set has 7718 in the cells where Punjab is located. In this way subdivisions can be ignored by dividing codes by 100. A single code identifies all water cells; Antarctica is treated as one entity.

2.2. *Land-Use Data Base*

A 1° digital data base of land-use practices was compiled by Matthews [1983] from approximately 60 published sources, primarily maps. Predominant land use was recorded for each cell in the data base. Classification criteria for this system emphasize variations in the intensity and permanence of surface modifications caused by anthropogenic activities and allow for the inclusion of crop combinations. A total of 119 land-use types are distinguished.

We used the land-use data base as our primary reference to locate grid cells having agricultural activities with which domestic animal populations are associated. Since this data base was designed to reflect global agricultural practices, it is not directly applicable to determining the distributions of domestic animals. Although grazing and livestock categories are explicitly included, they are not adequate indicators of the locations of animal populations since other land-use practices associated with animals may predominate in a cell. For example, only one cell is designated as having grazing in heavily agricultural India; the remainder of the country is classified as commercial or subsistence agriculture. We therefore assumed that domestic animals are associated with all agricultural activities. In practice, this meant excluding cells designated as 'no use' in the data base (about 50% of the global land area), as well as cells with the designation 'commercial lumbering' in North America, Europe, and northern Asia.

Two indices in the land-use data base corroborate the distribution of nonagricultural lands and, by implication, the distribution of agricultural lands. The first, a reliability index ranging from one to nine, reflects overall confidence in the source data for each cell. About 70% of the global land area is associated with reliability indices of seven or better. The 'no use' category in particular is characterized by high reliability indices. The second, a use intensity index from zero to five, was derived for each cell from a global series of 1:1M scale Operational Navigation Charts (Defense Mapping Agency, U.S. Department of Defense) with map dates from 1973 to 1983. A zero value indicates that no anthropogenic features of any kind are present; higher values indicate an increasing density of features ranging from minimal footpaths to dense complexes of roads, railroads, and cities. Over 90% of the global 'no use' area is associated with a use intensity index of zero or one.

The resulting distribution of agricultural cells shows reasonable qualitative agreement with land-use maps and dot maps of animal populations [e.g. Van Royen, 1954; *Atlas of Africa*, 1973; *Atlas of Australian Resources*, 1973; *Atlas of China*, 1973; *National Atlas of Canada*, 1973; *World Atlas of Agriculture*, 1969-1976; *National Atlas of India*, 1977; *1974 Census of Agriculture*, 1978; *Goode's World Atlas*, 1978]. Only minor modifications were required, i.e., a total of 14 cells were added to locate domestic animals properly in some remote regions, and 133 caribou grazing cells were added to the 216 existing ones based on information from *Goode's World Atlas* [1978], Anderson [1985] and Jackson [1986]. Altogether 6813 cells were targeted by the modified land-use data base.

2.3. *Animal Population Data Base*

Our primary source of population statistics for domestic animals was the *1984 FAO Production Yearbook* [FAO, 1985], which provides animal populations by country. For the seven subdivided countries we obtained regional data from other sources (see the appendix). Population statistics on wild and domestic caribou were compiled from Anderson [1978], Nowak and Paradiso [1983] and Jackson [1986].

Based on the CAS analysis of methane production by animals, we included the dominant methane-producing animals in our study: nondairy cattle, dairy cows, water buffalo, sheep, goats, camels, pigs, horses, and caribou. Reindeer are domesticated caribou and are herein referred to as caribou. Although caribou populations are relatively small, they were included in this study because they are the only significant animal methane source at very high latitudes. We did not include other wild and domestic animals and humans, which together are estimated to contribute only about 5% to the total animal source [CAS].

To obtain the geographic distribution of animals we used the modified land-use data base to locate agricultural cells in each country or subdivision. The population of each animal type was distributed at uniform density among those cells. If no agricultural cells were identified, we assumed a uniform concentration of animals within the political boundary. This occurred in only 83 cells, 43 of which are one-celled countries, mostly islands. The inclusion of these cells brought the total number of cells with animals to 6896. This method of distribution results in multiple animal types in each cell; the only exception is caribou, for which there are exclusive cells. Although the data base is at 1° resolution, the effective resolution of animal population densities is the size of the agricultural area in each political unit. The distributions of animal densities are discussed in section 3.

2.4. *Determination of Methane Emission*

Methane production from animals results from fermentation of carbohydrates in the digestive system. It is highest in ruminants, but occurs in virtually all animals. The production rate is dependent on energy intake, enteric ecology, and energy expenditure of the animal. Since the production rate is affected by factors such as quantity and quality of feed, body weight, age, and exercise, it varies among animal species as well as among individuals of the same species.

Recently, CAS presented a comprehensive assessment of methane production rates from animals. Gross energy intake for each animal type under several husbandry regimes was estimated based on available measurements. These intake estimates were combined with estimates of methane yields at different feed quality levels to obtain annual methane production for each animal type. For example, they estimated that the mean daily gross energy intake per animal is 260 MJ for milk cows in West Germany but averages only 60.3 MJ for all cattle types in West Bengal, India. The methane yield is 5.5% of the energy intake for the German dairy cows fed with high-quality feed at 2–3 times maintenance, and is 9% for the Indian cattle on low-quality feed at maintenance levels. With an energy content of 55.65 MJ/kg CH_4, the annual methane production per animal is 95 kg for the German dairy cows and 35 kg for the Indian cattle: a three-fold difference. Based on detailed German statistics, CAS reported that a substantial fraction (21%) of the bovines in West Germany are milk-fed calves that produce negligible methane, yet calves are not enumerated separately in the FAO statistics. CAS' analysis illustrates the inherent difficulty in obtaining global estimates of animal methane emission; they estimated an overall uncertainty of ±15% in the emission.

Using detailed information available for Germany and the USA, CAS estimated production rates for several cattle classes. For U.S. dairy cows, beef cattle on feedlots, and beef cattle on range, they obtained annual rates of 84 kg, 65 kg and 54 kg CH_4, respectively, yielding a weighted mean rate of 58 kg per animal. Based on this and the mean production rate of 57 kg calculated for all bovines in West Germany, and considerations of differing population characteristics in other developed countries, they derived a mean production rate of 55 kg for bovines in most developed countries.

In order to apply this information to our geographic data base, further assumptions were made. First, we designated countries, as did CAS, as having developed or developing economies using the FAO classification [FAO, 1985]. For Canada, we assumed that production rates for U.S. bovine classes apply. For Argentina, Australia, Brazil and South Africa, where cattle are mostly range fed, we used the annual rate suggested by CAS of 54 kg CH_4 for both dairy cows and nondairy cattle. For dairy cows in other developed countries, CAS indicated a lower production rate than that in Germany but did not cite a specific number. Therefore, we assumed a rate of 90 kg for dairy cows and adjusted the rate for nondairy cattle to obtain the mean rate of 55 kg derived by CAS. While these distinctions in the production rates do not affect the total global methane emission in the data base, they do have significant regional effects where, for instance, there are large proportions of dairy cows in the bovine population (see section 3). In developing countries, where the diets of dairy and nondairy cattle are similar, and where the animals tend to have lower body weight and less feed, the rate of 35 kg suggested by CAS was used for both populations.

Emission rates calculated by CAS were applied directly to other animal types. For sheep, the annual methane production rates of 8 and 5 kg in developed and developing economies, respectively, were used. As done by CAS, an exception was made for Australian sheep, to which the 5 kg rate was assigned because of their small size. The corresponding rates for pigs are 1.5 and 1 kg, respectively. Production rates for camels (58 kg), water buffalo (50 kg), goats (5 kg), horses (18 kg) and caribou (15 kg) were constant for all countries.

After each animal type in each country was assigned its corresponding methane production rate, the total methane emission per unit area was computed by adding together the sources in each cell. The resultant distribution of methane emission is discussed below.

3. DISTRIBUTION OF ANIMAL POPULATIONS AND METHANE EMISSION

A global annual emission of 75.8 Tg CH_4 by domestic animals was obtained for 1984, similar to the rate of 72.9 Tg calculated by CAS for 1983.

Global distributions of population densities of the major methane-producing animals are presented in Plates 1a-1h. These distributions form the framework for determining geographic variations of methane emission (Plate 2). For each animal type, Table 1 lists populations, population densities, and methane emissions for the countries with the largest animal populations.

The distributions of nondairy cattle and dairy cows are shown in Plates 1a and 1b, respectively. For bovines as a group (nondairy cattle and dairy cows combined), the highest populations and population densities are in the Indian subcontinent; 182 million, or 14% of the global total, occur in India. Densities reach 176 bovines/km^2 in the state of West Bengal and 120 bovines/km^2 in Uttar Pradesh. Bangladesh has 36 million, or 3% of the bovines in the world, as well as the highest density, 246/km^2. High bovine densities are also found in Europe, especially in the Benelux countries where densities reach 189 animals/km^2. By contrast, the density in Texas, which has 13% of the bovines in the USA, is only 24/km^2.

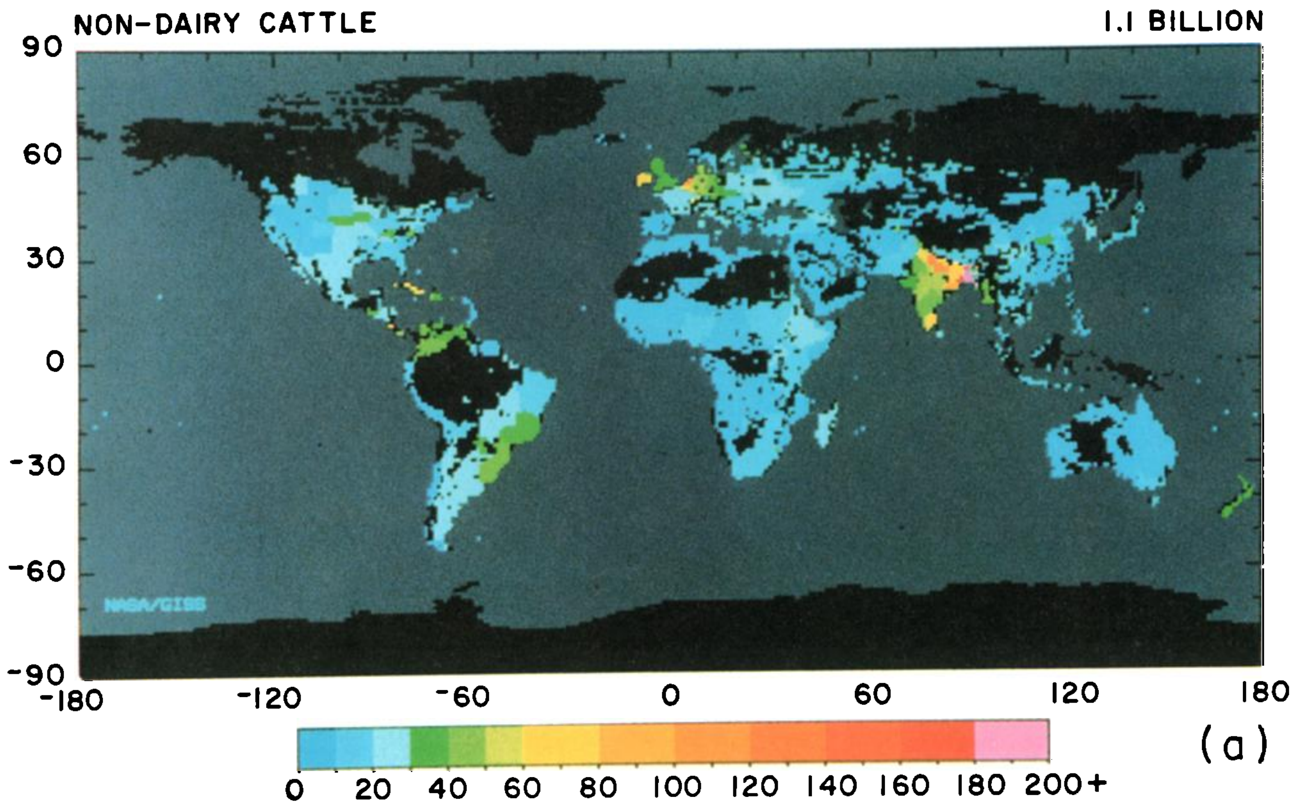
As found by CAS and other investigators, bovines are the major contributors to global methane emission by animals, accounting for 57 Tg or ~75% of the global total. As a consequence, the distribution of methane emission (Plate 2a) closely resembles the bovine distribution. For example, in Brazil, 7.2 of 7.5 Tg is emitted from bovines; a similar pattern occurs in the USA, where bovines account for 94% of the emission. However, in certain areas, methane emissions from other animals are nearly as important.

Water buffalo (Plate 1c) are found mainly in the southern parts of Asia, where they are used as draft and dairy animals. About half of the global population is in India (64 million), 15% in China, and 10% in Pakistan; highest concentrations are in the northern Indian states of Punjab and Haryana (89 and 72 heads/km^2, respectively). Although water buffalo contribute only 6.3 Tg to the global methane emission by animals, they account for 31% of the emission from India, 22% of that from China and 42% of that from Pakistan.

The global population of sheep (Plate 1d) is 1,136 million, of which 13% are in the USSR and 12% in Australia. Densities are highest in New Zealand (382 heads/km^2), Tadzhikistan (152), Bulgaria (152), and the United Kingdom (142). Sheep account for ~9% of the global methane produced by animals, and contribute significantly to emissions from certain countries; for example, they account for 59% of New Zealand's methane, 37% of Australia's, and 14% of the methane from the USSR, which has more than twice the sheep population of New Zealand. In many other countries with substantial sheep populations, such as South Africa, Turkey, Uruguay, the United Kingdom, Afghanistan, Romania, and Iran, sheep account for more than 25% of the methane emission.

Goats (Plate 1e) are concentrated mainly in the developing nations, where they provide milk, meat, hides, and mohair. About 18% of the population (81 million) is in India and 15% (68 million) in China; highest densities are in West Bengal and Bangladesh, with 92 and 82 goats/km^2, respectively. Only 3% of the global methane produced by animals comes from goats. However, in some African countries, goats contribute more than 10% to the methane emission.

Pigs, camels, and horses each produce about 1 Tg CH_4 annually. With some exceptions, they do not play a major role in methane emission from individual countries. Pigs (Plate 1f) are found in all but some Moslem countries, but there are very large variations in density from country to country. Because they are raised almost exclusively for consumption, their distribution reflects local dietary preferences. In the Netherlands, the density reaches 361 heads/km^2, but it is only 23/km^2 in France. More than



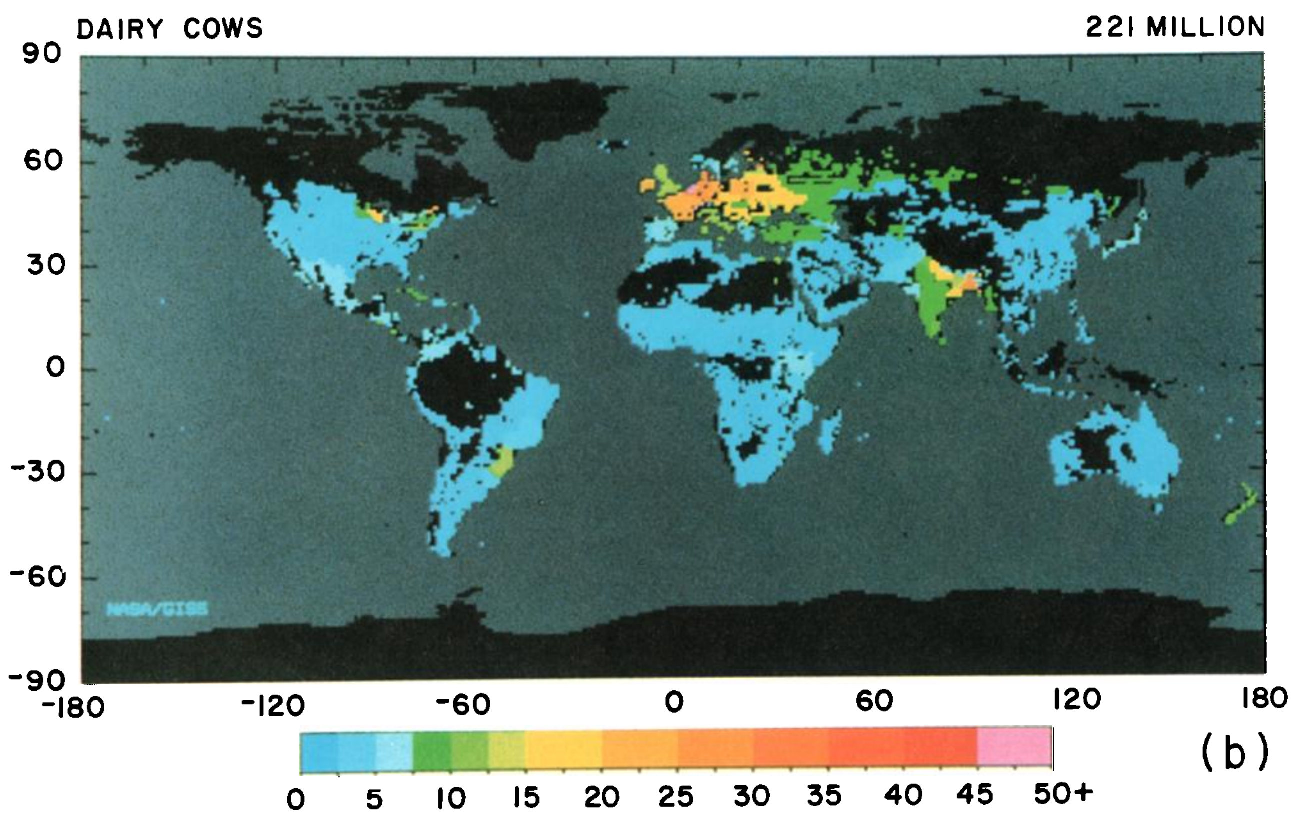
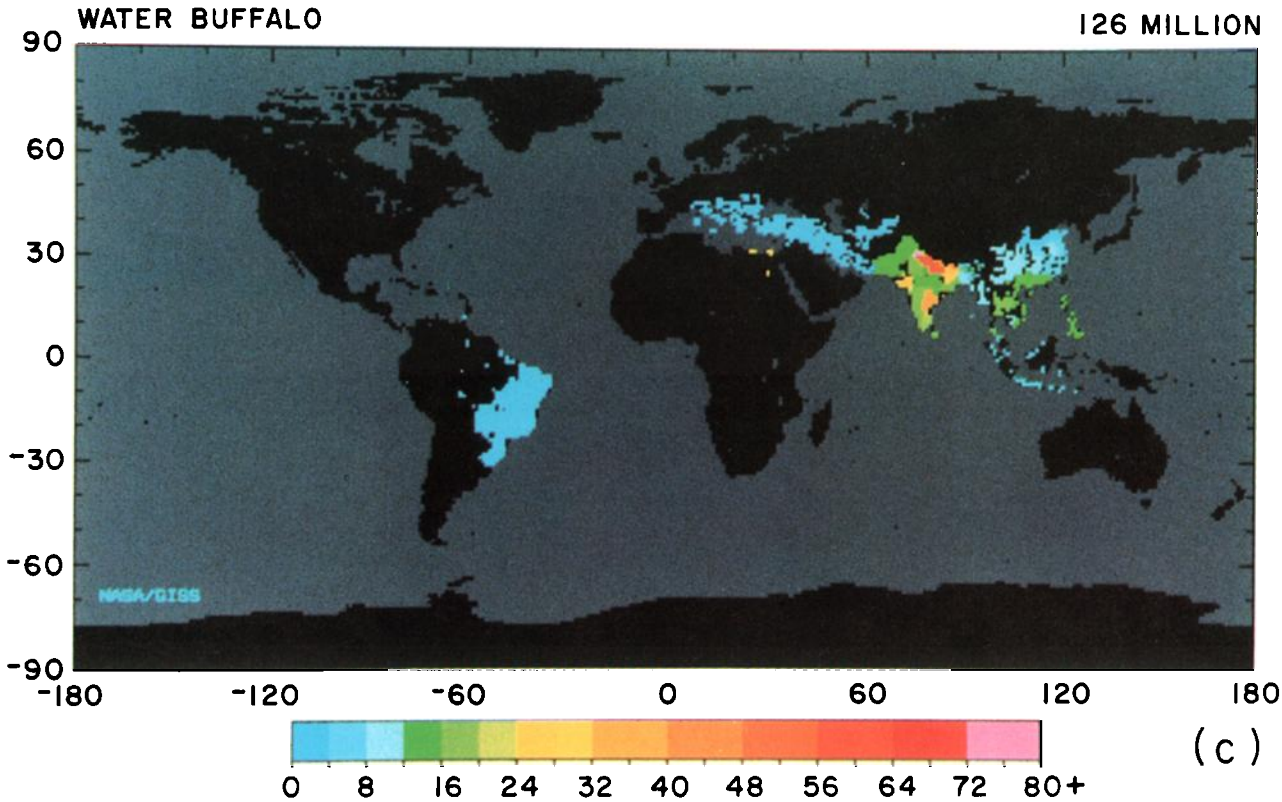
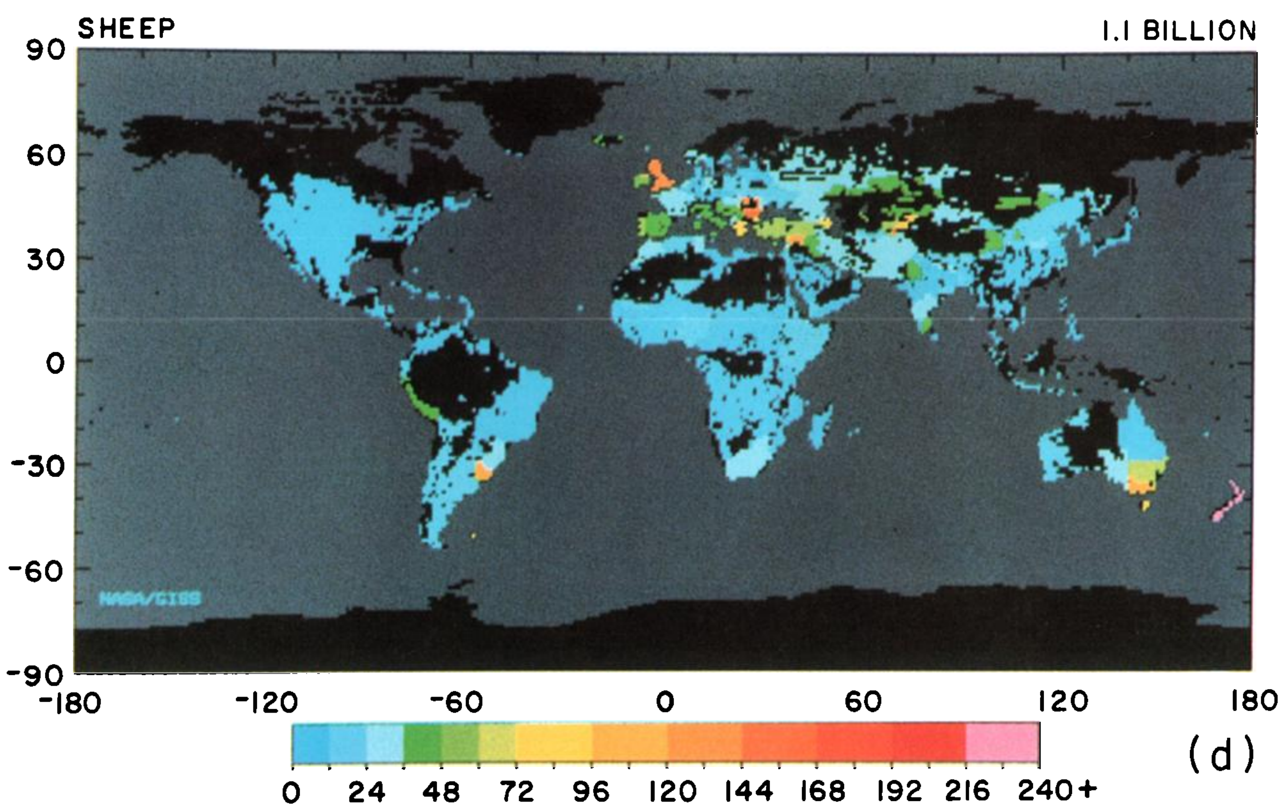


Plate 1. Population density of (a) nondairy cattle, (b) dairy cattle, (c) water buffalo, (d) sheep, (e) goats, (f) pigs, (g) camels, and (h) horses. Unit is animals per square kilometer. Global population for 1984 for each type is shown at top right of respective panels.





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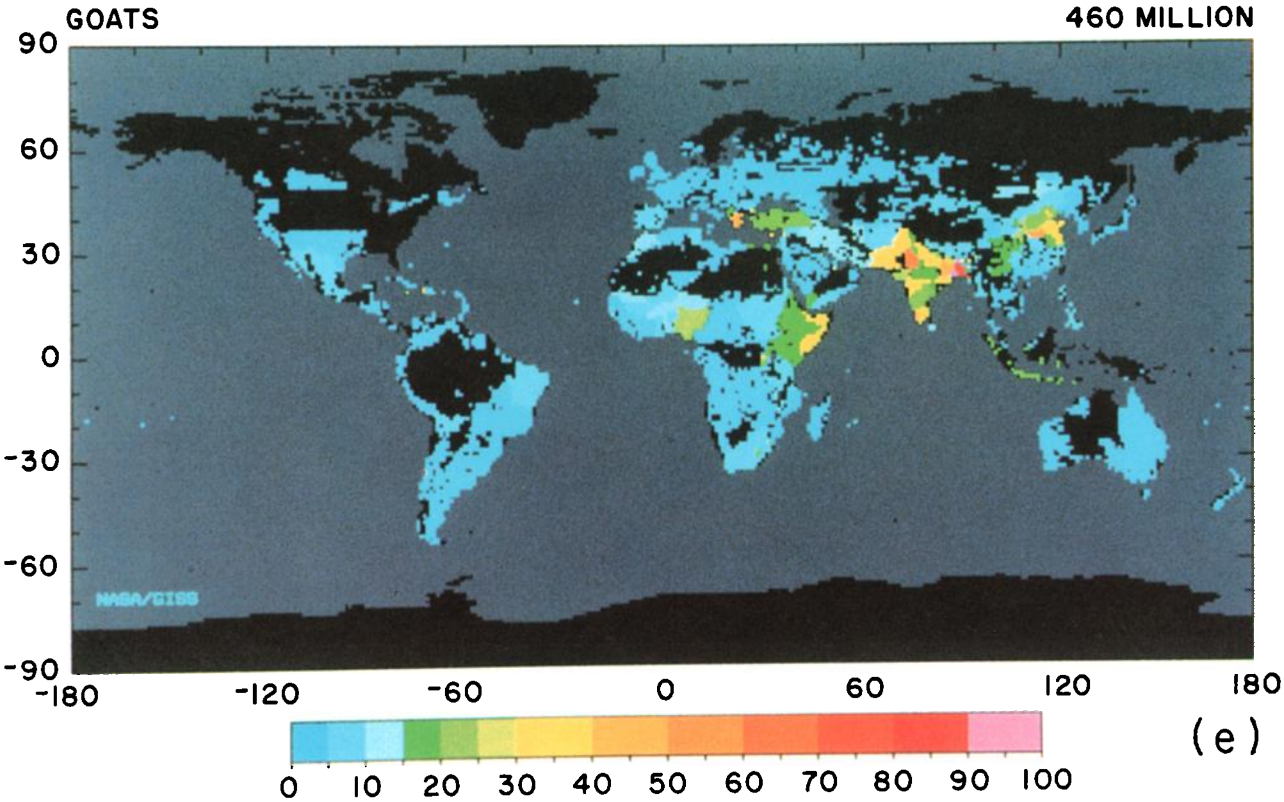

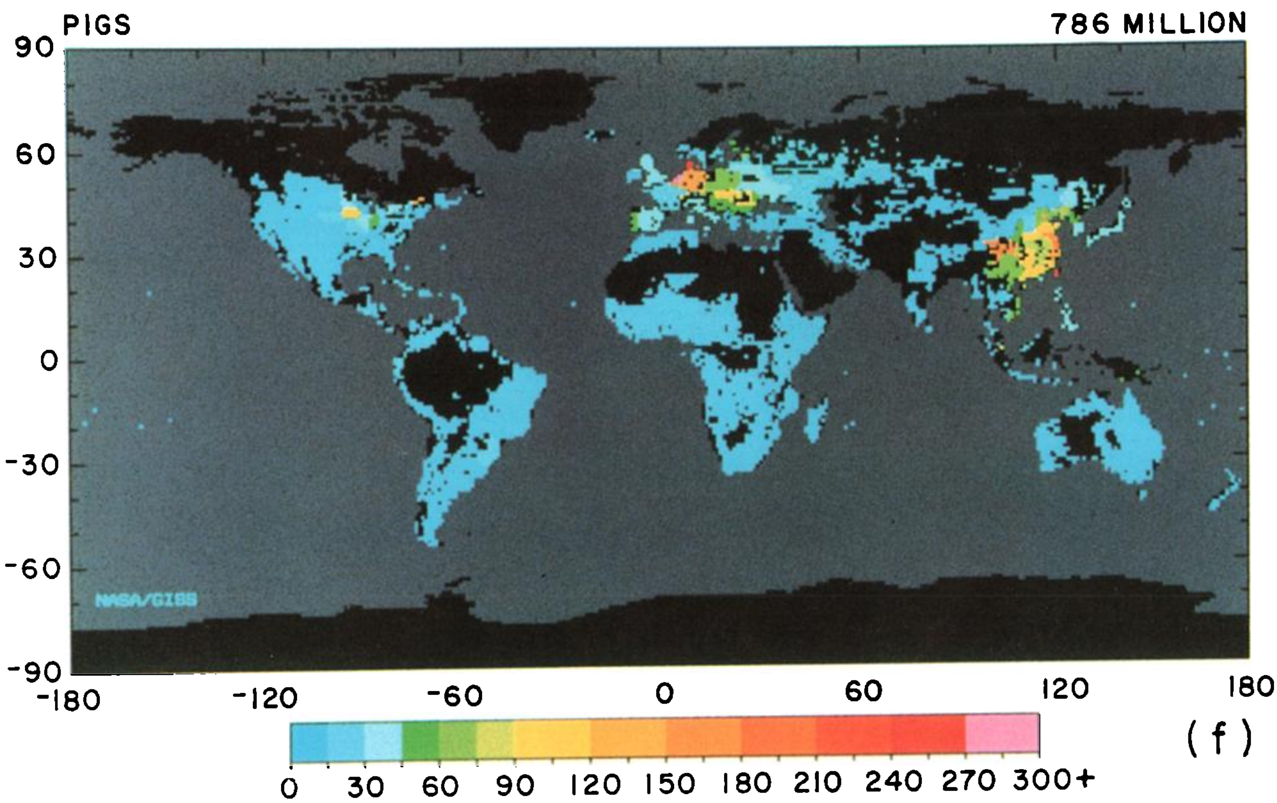

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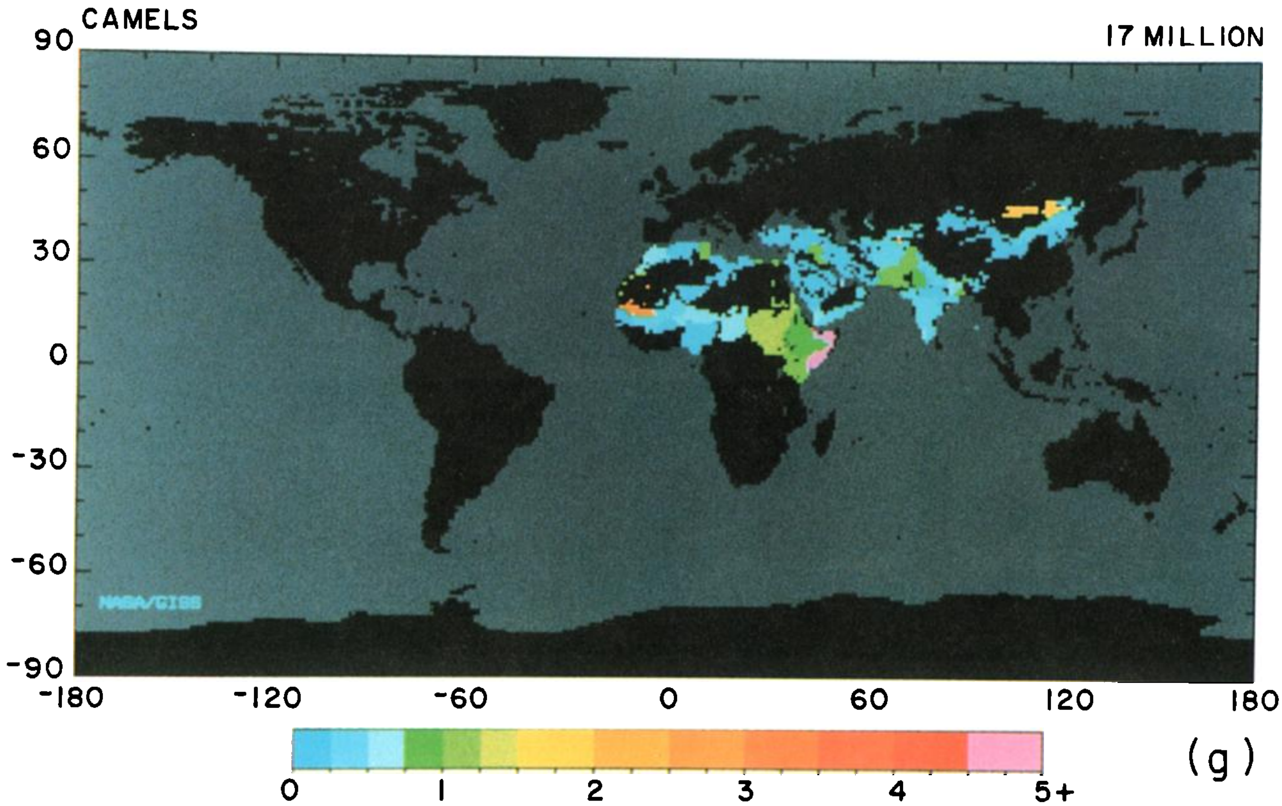

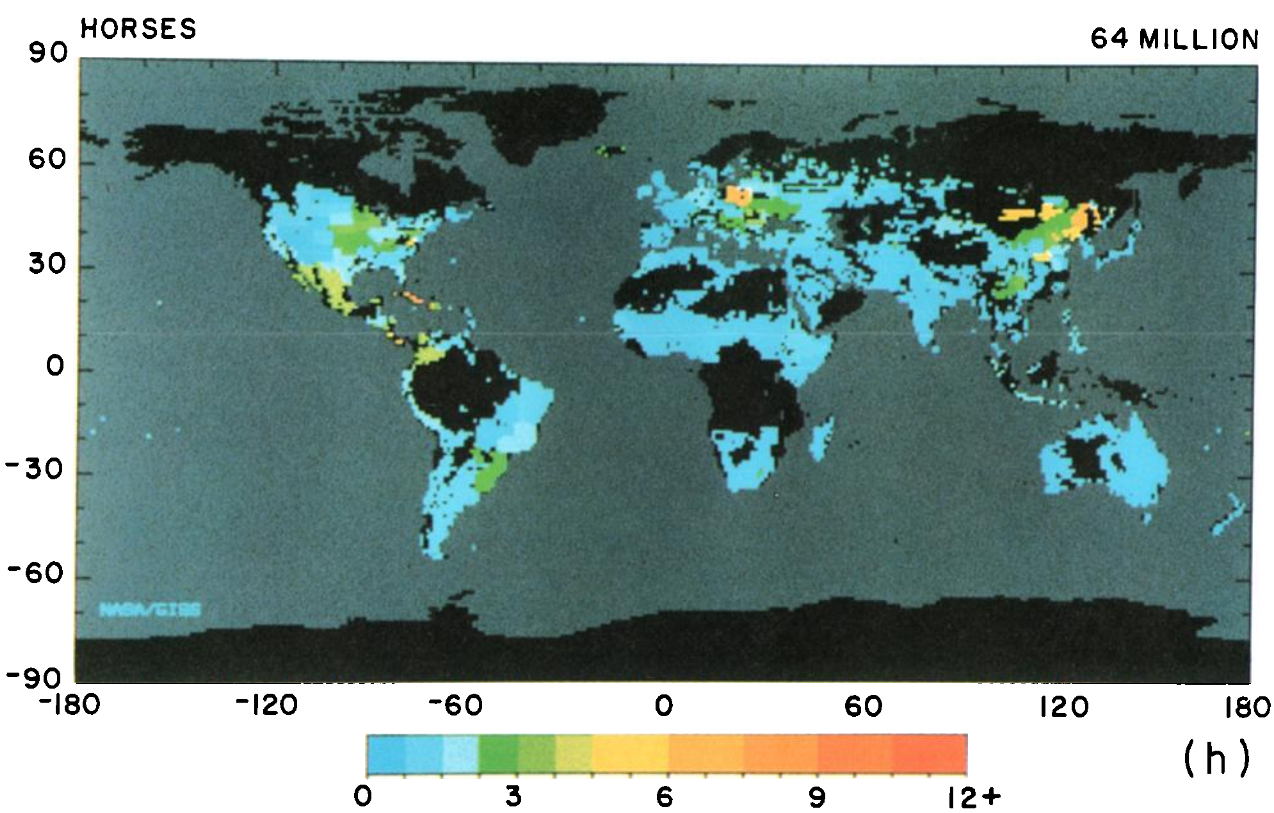

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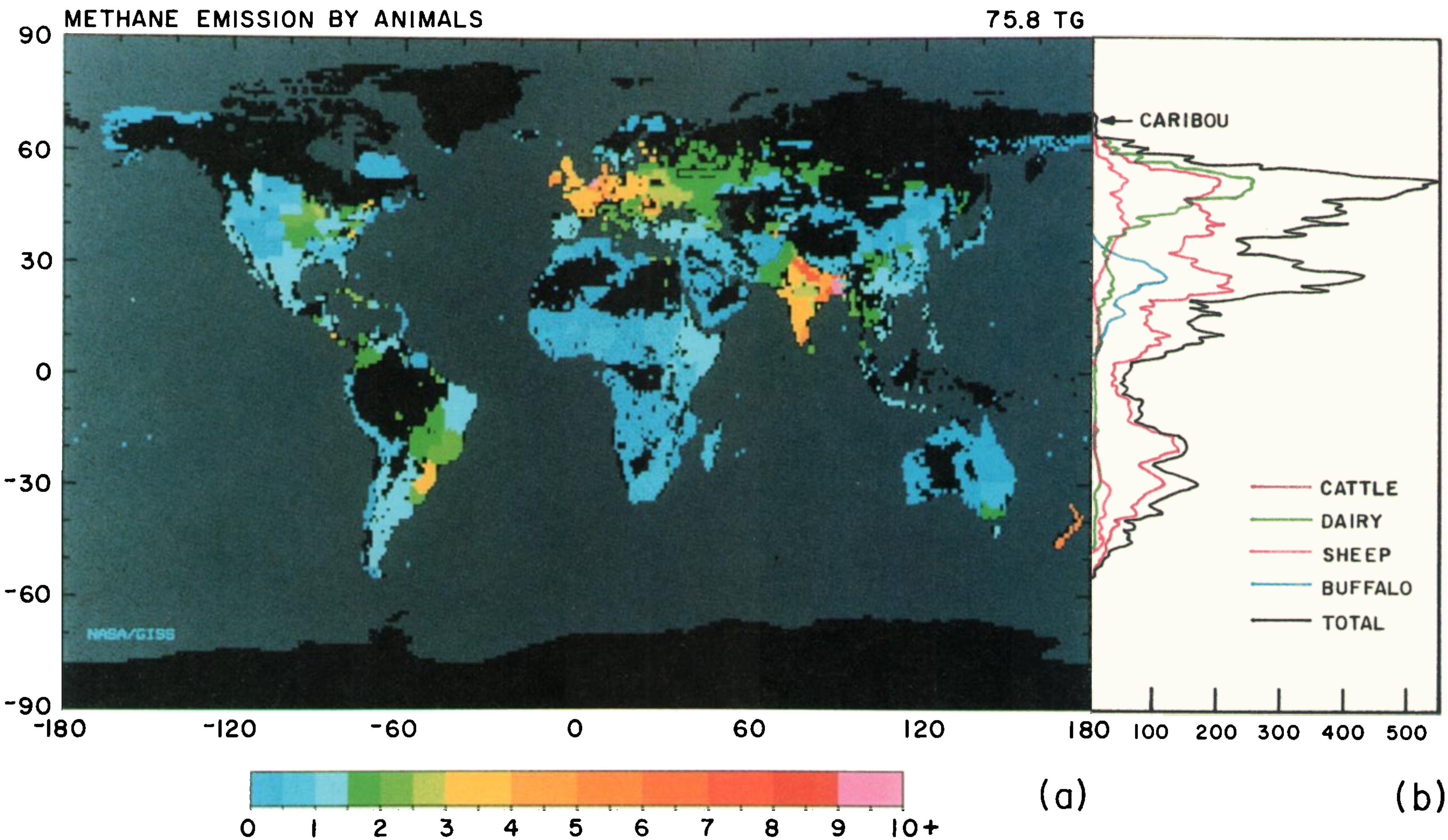

Plate 2. (a) Latitude-longitude distribution of methane emission from animals for 1984. Unit is 10^3 kg $CH_4/km^2/yr$. (b) Latitudinal distribution of zonal methane emission by animals and of methane emission by several animal types. Unit is kilograms per square kilometer per year.

TABLE 1. Population Statistics and Associated Methane Emissions for Seven Animal Types for 1984

	Population, Million		Density^{+}		Percent of Global Population		Methane Emission, Tg	
Bovines								
India	182.2		72 *		14.3		6.38	
Uttar Pradesh		29.0		120		2.3		1.02
Madhya Pradesh		24.9		59		2.0		0.87
Brazil	132.8		32 *		10.4		7.17	
Centro-Oeste		39.8		31		3.1		2.15
USSR	119.2		24 *		9.4		6.61	
Russia		59.5		24		4.7		3.35
USA	114.0		17 *		9.0		6.62	
Texas		14.4		24		1.2		0.81
China	58.5		10 *		4.6		2.05	
Argentina	53.5		25		4.2		2.89	
Mexico	37.5		30		2.9		1.31	
Bangladesh	36.3		246		2.9		1.27	
Ethiopia	26.0		23		2.0		0.91	
Colombia	23.9		48		1.9		0.84	
France	23.6		47		1.9		1.39	
Australia	22.2		4 *		1.7		1.20	
Water Buffalo								
India	64.0		25 *		50.8		3.20	
Uttar Pradesh		14.2		59		11.3		0.71
China	19.2		3 *		15.2		0.96	
Sichuan		3.3		11		2.6		0.17
Pakistan	12.8		16		10.1		0.64	
Thailand	6.2		20		4.9		0.31	
Nepal	4.4		45		3.5		0.22	
Sheep								
USSR	144.6		29 *		12.7		1.16	
Russia		63.4		25		5.6		0.51
Australia	139.2		25 *		12.2		0.70	
New South Wales		50.2		68		4.4		0.25
Western Australia		32.1		24		2.8		0.16
Victoria		24.4		103		2.1		0.12
China	98.9		17 *		8.7		0.50	
New Zealand	70.3		382		6.2		0.56	
Turkey	48.7		70		4.3		0.24	
India	40.9		16 *		3.6		0.20	
United Kingdom	34.8		142		3.1		0.28	
Iran	34.0		32		3.0		0.17	
South Africa	31.3		29		2.7		0.25	
Argentina	30.0		14		2.6		0.15	
Pakistan	24.3		30		2.1		0.12	
Ethiopia	23.5		21		2.1		0.12	
Uruguay	23.3		118		2.0		0.12	
Goats								
India	80.8		32 *		17.6		0.40	
Rajasthan		14.6		63		3.2		0.07
China	68.2		12 *		14.8		0.34	

TABLE 1 (continued)

	Population, Million	Density⁺	Percent of Global Population	Methane Emission, Tg
Pakistan	28.7	36	6.2	0.14
Nigeria	26.0	30	5.7	0.13
Ethiopia	17.3	15	3.8	0.09
Turkey	16.7	24	3.6	0.08
Somalia	15.7	31	3.4	0.08
Iran	13.6	13	3.0	0.07
Sudan	13.0	7	2.8	0.07
Bangladesh	12.1	82	2.6	0.06
Camels				
Somalia	5.7	11	33.1	0.33
Sudan	2.5	1	14.5	0.15
India	1.1	0	6.1	0.06
Ethiopia	1.0	1	5.9	0.06
Pakistan	0.9	1	5.2	0.05
Pigs				
China	298.7	52 *	38.0	0.30
Sichuan	51.5	167	6.6	0.05
USSR	78.5	16 *	10.0	0.12
Russia	39.1	16	5.0	0.06
USA	55.8	8 *	7.1	0.08
Iowa	14.8	95	1.9	0.02
Brazil	33.0	8 *	4.2	0.03
Sul	13.4	30	1.7	0.01
West Germany	23.4	121	3.0	0.04
Mexico	18.4	15	2.3	0.02
Poland	16.7	68	2.1	0.03
Romania	14.3	104	1.8	0.02
East Germany	13.1	143	1.7	0.02
Spain	12.4	33	1.6	0.02
France	11.4	23	1.4	0.02
Vietnam	11.2	63	1.4	0.01
Netherlands	11.0	361	1.4	0.02
Horses				
China	10.8	2 *	16.9	0.20
USA	10.3	2 *	16.1	0.19
USSR	5.7	1 *	8.9	0.10
Mexico	5.7	4	8.8	0.10
Brazil	5.2	1 *	8.1	0.09
Argentina	3.1	1	4.8	0.06
Mongolia	2.0	5	3.1	0.04
Colombia	1.9	4	3.0	0.03

Only the countries with the highest populations for each animal type are listed.
⁺Density is animals per square kilometer of agricultural area.
*Average density in a subdivided country.

TABLE 2. Total Annual Emission of Methane by Domestic Animals for Several Countries for 1984

	Methane Emission, Tg		Percent of Global Emission	
India	10.27		13.5	
Uttar Pradesh		1.79		2.4
Madhya Pradesh		1.24		1.6
USSR	8.05		10.6	
Russia		4.02		5.3
Ukraine		1.60		2.1
Brazil	7.46		9.8	
Centro-Oeste		2.17		2.9
Sudeste		2.09		2.8
Sul		1.51		2.0
Nordeste		1.39		1.8
USA	6.99		9.2	
Texas		0.85		1.1
China	4.37		5.8	
Argentina	3.11		4.1	
Australia	1.90		2.5	
Pakistan	1.54		2.0	
France	1.52		2.0	
Mexico	1.51		2.0	
Bangladesh	1.43		1.9	
Ethiopia	1.20		1.6	
Sudan	1.00		1.3	

Countries are listed in order of emission.

25% of the pigs in the USA are raised in Iowa, which has 14.8 million. Of the global total of 786 million pigs, 38% are in China, contributing 7% to the methane emission from that country. Camels [Plate 1g] are concentrated in two countries: one-third are in Somalia and 15% in Sudan. Population densities are generally low, the highest being 11 heads/km^2 in Somalia. Although the global methane emission from camels is only 1 Tg CH_4, their predominance in Somalia results in their contributing 57% to the Somalian emission. China and the USA have the largest populations of domestic horses, accounting for 17% (11 million) and 16% (10 million), respectively, of the global population (Plate 1h).

We do not show the caribou distribution per se, but the methane emission from caribou is represented in Plate 2a as the low emission density in Alaska, Canada east of Hudson Bay, and other areas north of the Arctic Circle. Russia has the largest population, about 2.6 million, many of which are domestic [Anderson, 1978; Nowak and Paradiso, 1983]. The largest single wild herd, over 660,000 animals, is in Quebec and Labrador [Jackson, 1986].

The results discussed above and shown in Plates 1 and 2 highlight the large spatial variation in the abundances of domestic animals and the impact of these variations on methane emission. Population patterns vary considerably among animal types. These variations are partly dictated by climate and vegetation, but also strongly reflect local culture, history, and economic conditions. Because of the differences in population patterns, the contribution of each animal type to the total local emission varies from country to country. In China, the fifth most important country for animal emissions (Table 2), bovines account for only 49% of the methane, while the remainder is made up by buffalo (22%), sheep (11%), goats (8%), pigs (7%) and horses (4%). Omission of the contributions from these other animals would significantly underestimate the local emission.

India alone accounts for 14% (10.3 Tg) of the global source (Table 2), of which cattle contribute 6.4 Tg, and water buffalo 3.2 Tg. Therefore, about 14% of the total methane source from animals is emitted from just 0.6% of the surface area of the globe. Emission rates exceed 5,000 kg CH_4/km^2 annually in many parts of India, and reach 9,702 kg/km^2 in Bangladesh.

Western Europe has some areas of high methane emission but its total contribution to the atmosphere is less than that of the USA. The United Kingdom and western Europe combined produce about 6.2 Tg, more than half of which comes from France, West Germany, and the United Kingdom. However, the high concentration of bovines (especially dairy cows) in the Benelux nations makes them important point-like sources of methane; the global maximum annual emission rate of 11,356 kg/km^2 occurs in this area.

The latitudinal distribution of methane emission reflects the localized character of the animal sources of methane. About 76% of the methane emission from animals occurs in the northern hemisphere. Zonally averaged emission rates show a peak of ~540 kg/km^2 around 50°N, and a secondary peak of ~430 kg/km^2 around 25°N (Plate 2b). The emission at most latitudes is dominated by cattle except at ~50°N, where the emission from dairy cows dominates. Although the emission from water buffalo is only 8% of the global total, they are concentrated in a narrow latitudinal zone and contribute ~25% to the emission between 20°N and 30°N (Table 3). Sheep contribute significantly to the total methane from 30°S to 50°S and from 25°N to 60°N.

4. DISCUSSION OF UNCERTAINTIES

FAO and the other sources of animal statistics (see appendix) give animal populations in units of thousands. Assuming that normal rounding procedures are used, the uncertainty for each animal type in each country is ±500 animals. For a country listed as having 1000 of a particular animal the uncertainty is then 50%. Globally, for 187 countries the uncertainty is $\pm 500 \times \sqrt{187} = \pm 6{,}837$ animals for each animal type, which is less than 0.1% of the total. Additionally, animal population statistics in FAO production yearbooks are often estimates which are modified in subsequent yearbooks. The *1983 FAO Production Yearbook* [FAO, 1984] cites a global total of 1,225 million cattle, but the *1984 FAO Production Yearbook*

TABLE 3. Latitudinal Distribution of 1984 Methane Emission by Different Animal Types and of Total Annual Methane Emission by Domestic Animals

Latitude	Cattle	Dairy	Buffalo	Goats	Sheep	Camels	Pigs	Horses	Caribou	Total
90-80N	-	-	-	-	-	-	-	-	-	-
80-70N	-	-	-	-	-	-	-	-	0.00	0.00
70-60N	0.14	0.23	-	0.00	0.06	-	0.01	0.01	0.05	0.49
60-50N	3.16	4.29	-	0.02	0.95	0.00	0.19	0.10	0.02	8.73
50-40N	5.60	4.67	0.04	0.16	1.44	0.06	0.28	0.31	-	12.55
40-30N	5.67	1.17	0.96	0.52	1.28	0.11	0.20	0.21	-	10.11
30-20N	7.56	1.23	3.50	0.61	0.39	0.11	0.17	0.15	-	13.71
20-10N	4.00	0.61	1.41	0.40	0.37	0.29	0.03	0.08	-	7.20
10N-0	3.06	0.43	0.28	0.33	0.28	0.40	0.02	0.07	-	4.87
0-10S	1.87	0.33	0.11	0.12	0.11	0.02	0.02	0.04	-	2.61
10-20S	3.97	0.29	0.01	0.06	0.17	-	0.01	0.05	-	4.57
20-30S	4.10	0.46	0.01	0.05	0.49	-	0.02	0.06	-	5.18
30-40S	2.74	0.31	0.00	0.02	0.91	-	0.01	0.05	-	4.05
40-50S	0.92	0.19	-	0.01	0.46	-	0.00	0.02	-	1.59
50-60S	0.13	0.01	-	0.00	0.02	-	0.00	0.00	-	0.16
60-70S	-	-	-	-	-	-	-	-	-	-
70-80S	-	-	-	-	-	-	-	-	-	-
80-90S	-	-	-	-	-	-	-	-	-	-
Global	42.94	14.21	6.31	2.30	6.91	1.00	0.96	1.15	0.07	75.83

Unit is teragrams CH_4 per year.

[FAO, 1985] lists 1,260 million for 1983, a 3% difference. As there is no way to improve or verify these statistics beyond what has been done by the FAO, we assume that the 1984 statistics are accurate to 3% globally. This uncertainty is small compared to the 15% uncertainty in the methane emission estimate cited by CAS.

Errors in the distribution of animals can come from the uncertainties in the locations and extents of agricultural areas indicated by the land-use data base used here. The reliability of the land-use data base is discussed in section 2.2. Published dot maps of animal distributions [e.g., Van Royen, 1954; *World Atlas of Agriculture*, 1969–76; *Goode's World Atlas*, 1978] display one dot per 5000, 10,000, or even 500,000 animals and are useful only on a qualitative basis; regions with low densities or few animals are underrepresented, while high-density regions are often saturated with symbols. Nevertheless, visual comparisons between these maps and the distributions derived here show good agreement in both the location and density of animals.

Quantitative estimates of the distributional errors are difficult to assess, especially where the land-use data base indicates that a large number of cells in a country or political subdivision are not agricultural. A special case is the Norte region in the Brazilian Amazon, where 12 out of 294 cells were used. In its state of Rondonia, the area of deforested land increased from ~4200 km^2 in 1978 to ~17,000 km^2 in 1984 [Malingreau and Tucker, 1988], an increase in area about equal to the size of a 1° cell. The land-use data base cannot capture this rapid conversion of forests to rangelands. For this study, agricultural cells were added to Rondonia to reflect the 1984 conditions in the Amazon. However, this has an insignificant effect on the animal distributions because less than 4% of Brazil's domestic animals are in the region.

The accuracy of the animal distributions is additionally dependent on the size of a political unit, which is the effective resolution of the animal data base. The use of subdivisions for the large countries improved the resolution of the data base. For example, in India (25 divisions), bovine density varies from 6 to 176 animals/km^2 in Nagaland and West Bengal, respectively, whereas with no subdivisions the average for the entire country is 72 bovines/km^2. The subdivisions used here appear adequate for all countries except the USSR, where the republic of Russia occupies 2920 cells encompassing 17 million km^2. The land-use data base targets 342 agricultural cells encompassing 2.5 million km^2, and animal populations for Russia were distributed uniformly over this area. Although the agreement with dot maps is good, it is unlikely that the animal density is even approximately uniform over such a vast area, but we are not aware of more detailed regional data.

To emphasize the importance of using both the country and land-use data bases together to derive the animal methane distribution, we present results from five case

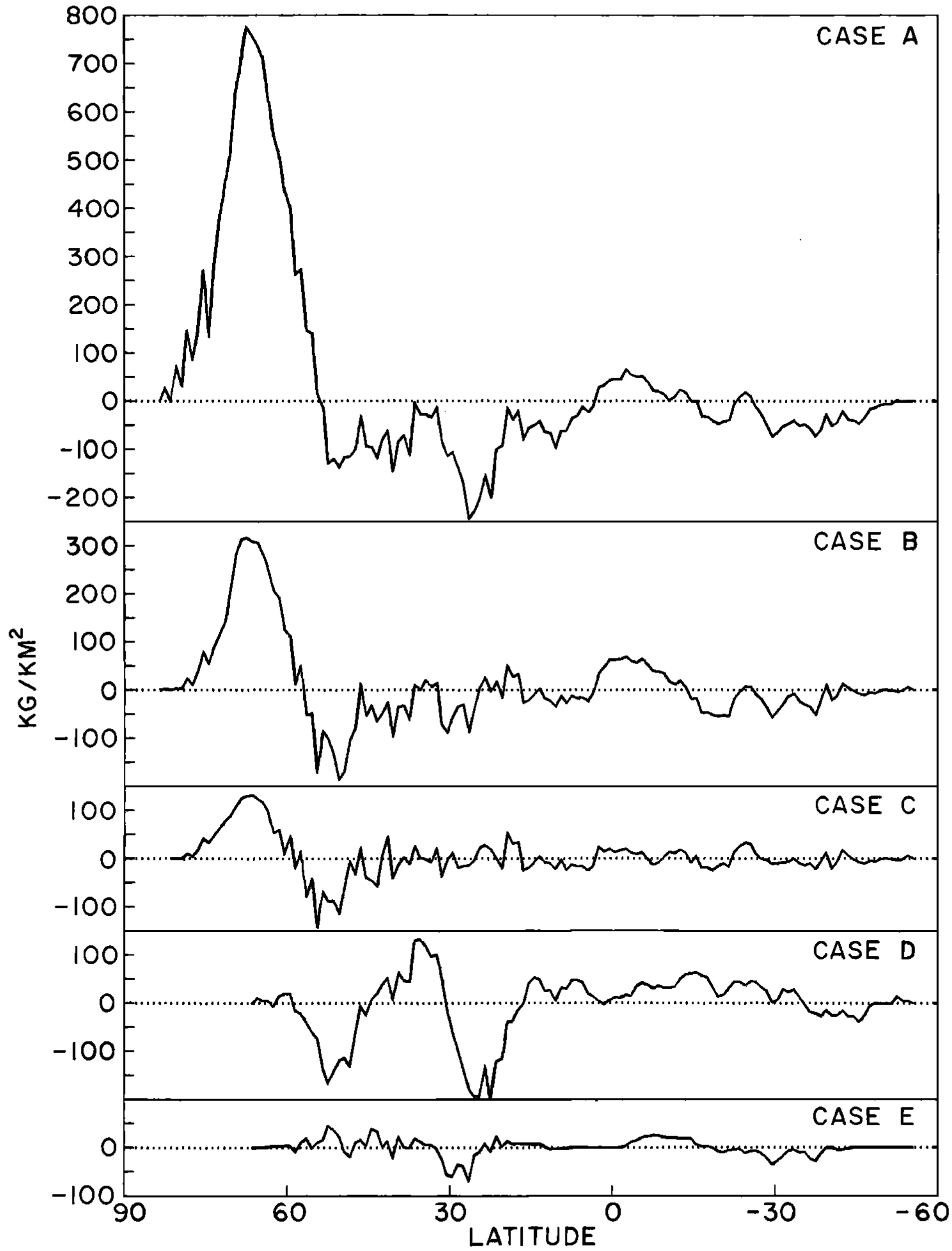

Fig. 1. Comparison of the latitudinal distribution of anomalous methane emission rates obtained using alternate mapping methods. The emission anomalies are defined as departures from the distribution presented in Plate 2b. See text for explanation of the cases.

studies using less precise mapping methods. In all cases we excluded animals from ice-covered regions and did not include caribou. Methane emission was calculated using the emission rates and animal populations discussed above, so that the global total was the same in all cases. Resulting latitudinal distributions of methane emission for each case were calculated and compared with the distribution described in section 3 and shown in Plate 2b. The differences between the distribution in each case study and the results presented in section 3 and Plate 2b are shown in Figure 1.

The first three cases (A–C) evaluate the adequacy of the country data base alone on computation of the distribution of methane emission; the land-use data base was not used. In case A, the global total of each animal type was distributed uniformly over all ice-free land. In case B, the country data base without subdivisions was used and animals were distributed evenly within the boundaries of their respective countries. In the third case (C), the complete country data base, including subdivisions, was used. Results from all three cases are dominated by the expected overestimate of emission from the cold northern areas of North America, Russia and Scandinavia, with a corresponding underestimate from the more densely populated temperate and subtropical zones. Case C, with the seven large countries subdivided, is the most reasonable of the three. The overestimate between the equator and 15°S in cases A and B, which is primarily caused by unrealistically high concentrations of animals in the Amazonian rainforest, is corrected by subdividing Brazil. However, while the number of animals north of 60°N is reduced in case C, the concentration is still very unrealistic at those latitudes.

The results of case C suggest that improvement in the distribution of animals would result if each political unit (especially Russia) were further subdivided, for example, to the county level. However, this is impractical, since the data on animal populations are not always available. The land-use data base provides a reasonable alternative to further subdivisions.

Case D evaluates the adequacy of the land-use data base alone on the distribution of methane emission. The global total for each animal type was distributed uniformly over the agricultural locations indicated by the land-use data base so that each cell used had an equal density of animals; as in case A, the country data base was not used. The most important effect of the land-use data base is to shift the distribution of animals southward from the high northern latitudes, so that the overestimates of methane emission north of 60°N in cases A–C are eliminated. Also, deserts and rainforests are delineated, although this cannot be seen on the latitudinal plot. The large deficits around 25°N (also prominent in case A) and 50°N are caused by the redistribution of the large emissions from India and Europe.

Case E, like case D, used the land-use data base but animals were allocated to their respective countries; country subdivisions were not used. While the resulting distribution is similar to that shown in Plate 2a, there remains a small underestimate around 25°N, caused primarily by the lack of subdivisions in India. Case E also fails to capture longitudinal variations in the large countries. For example, half the bovines in the USSR reside in the small western republics, which together comprise less than 25% of the area of the country. Incorporating subdivisions of the large countries, as was done in the final results, ensures that steep latitudinal and longitudinal emission gradients, reflecting large spatial variations in animal densities, are captured in the data base.

As stated previously, the largest uncertainty in the geographic distribution of animal methane emission is the magnitude of emission rates from animals. An appreciation of the uncertainties contained in these figures may be obtained from the detailed discussion of the methodology used in deriving these emission rates in CAS. Clearly, uncertainties in the emission rates from different cattle classes will have the largest impact on the magnitude and distribution of the methane source. In developed countries, large-scale commercialization of cattle raising has reduced the diversity in the feed and body weight of animals. It is therefore reasonable to expect that estimates of methane emissions derived from measurements on a few animals may be representative of a large population. In developing countries, the highly variable diet, size, and use of animals probably give rise to a wide range of emission rates. However, there is little information to document this variability. At the annual emission rate of 35 kg CH_4/head as derived by CAS, these bovines contribute 31% to the global animal methane source. We investigated the effect of an alternate annual emission rate of 45 kg/head for these bovines, which is within the range of 40–50 kg/head/yr cited by Seiler [1984] for developing countries. This resulted in a 9% (6.6 Tg) increase in global emission, concentrated between the equator and 30°N, an increase that is comparable to the total contribution from sheep or from water buffalo. Thus, new measurements of methane emission by these animals or a change in husbandry practices could result in a significant change in both the distribution of animal methane and the global emission rate.

5. CONCLUDING REMARKS

There are reasonably reliable statistics on populations of domestic animals because of their economic importance. This makes possible a direct accounting of their methane emissions, within the uncertainties of the emission rates, as done by CAS. The animals' contribution is one of the better known terms in the global methane budget. Unfortunately, it is only ~20% of the global source. There is less well-documented information about many of the other methane sources, so that a direct estimate of the source strengths may contain uncertainties as large as the estimated strengths themselves. Constraining the magnitudes of these other sources will require information other than the global budget. Such ancillary information includes the isotopic composition of atmospheric methane and its sources, and the temporal and geographic variations of methane in the atmosphere. Determination of the geographic distribution of the animal source is a crucial step in using the geographic variations in atmospheric methane to infer information about the global budget.

There is large spatial variability in the distributions of animal populations and their methane emission. About half of the annual global emission of 75.8 Tg comes from only five countries: India, the USSR, Brazil, the USA, and China; most of the remainder comes from over a hundred countries, each of which contributes on the average <0.5 Tg. Emission rates greater than 5000 kg CH_4/km^2 are found in small regions such as Bangladesh, the Benelux countries and New Zealand, while large portions (>50%) of the global land area have sparse populations of domestic animals and negligible animal sources of methane.

Nondairy cattle and dairy cows together contributed 57 Tg or 75% of the total animal source in 1984. Other animals with small populations or with low emissions are nevertheless important contributors to local methane budgets. For example, sheep account for 9% of the global source, but for 59% and 37% of the total source from New Zealand and Australia, respectively. Similarly, water buffalo, which contribute 8% of the global emission, account for 31% of the emission from India.

Emission peaks from 35°–50°N are from cattle and dairy cows in the USA, the USSR and western Europe. A secondary peak in emission is found in the subtropics, between 10°–30°N, emanating mainly from bovines and water buffalo in the agricultural countries of south and southeast Asia.

About 76% of the animal methane source comes from the northern hemisphere. This interhemispheric asymmetry will contribute significantly to the north-south gradient in the observations of atmospheric methane [Steele et al., 1987]. Furthermore, large longitudinal variations in atmospheric methane will result from the dramatic spatial variations in the sources. Until recently, sampling of atmospheric methane has been largely confined to remote marine sites. Better definition of the sources of methane will require sampling near source regions, some of which are identified in this study.

APPENDIX

FAO production yearbooks provide annual statistics, by country, for populations of cattle, dairy cows, water buffalo, pigs, sheep, goats, horses and camels. In this appendix, we discuss the distribution of only those animals in each subdivided country whose populations are reported in the 1984 yearbook. In addition to FAO animal population statistics, data on animal populations were obtained for subdivisions of the seven largest countries. As described in section 2.3, animals were uniformly distributed among the agricultural land-use cells within each smaller unit of a country. For some animal types, data for subdivisions were not available. In those cases, we distributed FAO country-wide totals in proportion to other animal types or according to distributions shown in dot maps [e.g., Van Royen, 1954; *World Atlas of Agriculture*, 1969–1976; *Goode's World Atlas*, 1978]. When data for the subdivisions were from a year other than 1984, they were scaled to conform with statistics from the *1984 FAO Production Yearbook* [FAO, 1985].

Australia

Population statistics for the states were obtained from the *Australian Encyclopedia* [1979] (bovines and sheep), and from the *Atlas of Australian Resources* [1973] (dairy cows and pigs). The nondairy cattle population for each state was derived as the difference between bovines and dairy cows. The FAO goat population of the country was distributed in proportion to the number of sheep in each state; the FAO horse population was distributed in proportion to cattle plus sheep.

Brazil

Statistics for bovines, water buffalo, pigs, horses, sheep, and goats are listed for each of the 26 states in the *Anuario Estatistica do Brasil–1984* [1985], and are grouped into five regions. Since the animal populations within each state of a region are approximately proportional to the area of the state, the five regions were considered sufficiently small for our purposes. No regional statistics were found for dairy cows; the FAO total was distributed in proportion to pigs. The dairy cows were then subtracted from total bovines in each region to yield the distribution of nondairy cattle.

Canada

Of the provinces and territories of Canada, New Brunswick, Nova Scotia and Prince Edward Island were combined into one unit. Provincial populations of cattle, dairy cows and sheep were obtained from *Livestock and Animal Product Statistics: 1984* [1984]. The FAO goat population was distributed in proportion to sheep, pigs were distributed in proportion to dairy cows, and horses were distributed in proportion to cattle plus dairy cows.

China

Statistics for each animal type for the 29 provinces of China were obtained from *Agricultural Statistics of the People's Republic of China, 1949–1982* [1984]. The data used were from 1981 and 1982. Taiwan's animals are not included in these statistics, although Taiwan is treated as part of China by FAO. As the data are from different years, the animal population of Taiwan cannot be derived from these two sources. We therefore used data on Taiwan listed in *Agricultural Statistics 1984* [1984], which generally agrees with FAO in other respects. These data were subtracted from the FAO statistics for China before scaling the regional 1981/1982 China data to conform with the FAO 1984 country-wide totals. In this way the global total of animals was not altered.

India

Populations of bovines, water buffalo, horses, sheep, and goats are listed by state in *Agriculture in Brief* [1977]. The FAO dairy cow population was distributed in proportion to bovines. Nondairy cattle were then calculated as the difference between bovines and dairy cows in each state. Camels (from FAO) were distributed in proportion to goats. Pigs (from FAO) were distributed in proportion to bovines in the few states indicated by a dot map in *Goode's World Atlas* [1978].

USA

Agricultural Statistics 1984 [1984] contains listings of nondairy cattle, dairy cows, sheep, and pig populations by state. Goats (from FAO) were distributed according to text and a dot map in *The Agricultural Resources of the*

World [Van Royen, 1954] and data on goat shearing from *Agricultural Statistics 1984*. Horses (from FAO) were distributed in proportion to cattle plus dairy cows.

USSR

Statistics, by republic, were obtained from *Europa Year Book 1985* [1985] for total bovines, goats-plus-sheep, pigs, and milk production. The number of dairy cows in each republic was derived by distributing the FAO country total in proportion to milk production in each republic. The dairy cows were then subtracted from total bovines in each republic to yield the distribution of nondairy cattle. The country-wide ratio of goats to sheep was derived from FAO and assumed to be constant for each republic. This ratio was used to calculate the goat and sheep populations from the goats-plus-sheep figures for each republic. Horses (from FAO) were distributed in proportion to cattle plus dairy cows. FAO totals for camels and water buffalo were distributed in southern republics.

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